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Regular Article

Effects of horizontal seismic band on seismic response in masonry structure: Application of DIC technique



Santosh Yadav^{a,*}, Hala Damerji^a, Reinold Keco^a, Yannick Sieffert^a, Eugénie Créte^b, Florent Vieux-Champagne^a, Philippe Garnier^b, Yann Malecot^a

^a Univ. Grenoble Alpes, Grenoble INP, CNRS, 3SR, F-38000 Grenoble, France

^b Laboratoire CRAterre, Unité de recherche AECC, École Nationale Supérieure d'Architecture de Grenoble, France

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ABSTRACT

Masonry construction is one of the oldest building systems and practiced since the early stage of human civilization. Even though industrialized nations developed new building practices using steel and concrete materials, most developing countries still use unreinforced masonry buildings. Evidence from past events shows that masonry structures sometimes performed well and survived several earthquake events, particularly in the area where earthquake events struck regularly and enough to show how structures behave. However, an alteration from the traditional cultural building practice is seen due to the lack of proper scientific knowledge about such local construction cultures. Amongst traditional construction technics, one captured authorities' and scientists' attention as showing excellent properties: seismic bands that can be found in many parts of Nepal. After the 2015 Gorkha earthquake, reconstruction works started adopting the guidelines developed by DUDBC and National Building code that suggest using such seismic bands. The evidence of using such band dates to 2500 BCE, and qualitative studies of those applications have proven to enhance the performance in the masonry structure. However, the experiment's quantitative parameters using various materials are needed to carry out the parametrical analysis to optimize seismic band's use. To provide quantitative results, we have started with two specimens, one without a band and one with a timber seismic band, and incorporate the digital image correlation (DIC) technique to obtain the localized information. The quasi-static cyclic test is carried out for our specimens to compare the behavior concerning the energy dissipation, and the surface area of the crack formed during the loading cyclic. This work clearly shows the seismic band's advantage in limiting the crack propagation and improving masonry structure integrity.

1. Introduction

Masonry structures constitute the oldest buildings constructed by human civilization and their technic evolved with cultural values and way of living. As per the world population statistics, approximately 86% of the world population is present in the underdeveloped and developing nation [1]. According to the United Nations, half of these population live in building constructed using earth materials (rammed earth, kneaded earth, adobe, wattle, and daub, cob, etc.). [2] carried out a basic SWOT (Strengths, Weakness, Opportunities, Threats) analysis for the earthen structures and found several benefits of using such construction material. Such construction practices not only preserve the socio-cultural aspect but also has economic and environmental gain.

With the increasing construction trend using concrete and steel structures, people have started forgetting their traditional construction practices and adopting new materials without proper technique. When we look at the

global seismic hazard map, most densely populated countries with weak financial conditions are located in the seismically active zone [3]. There is evidence showing that some traditional buildings survived several events of an earthquake. At the same time, sometimes modern RC structures collapsed [4]. Despite that, traditional cultural constructions seem to be fading out and being replaced by modern construction technics. Some questions are emerging- is the current construction practice sustainable, did we miss to understand better and study our traditional building practice?

To better understand the traditional cultural practice, several research works have been carried out. [5] has highlighted that the earthquake-resistant traditional construction is not an oxymoron with the examples of structures that survive during a disaster event in various parts of the world. Many works have been carried out to enhance masonry structures' strength using retrofitting techniques [6–10]. Some of these techniques required skilled labor for an effective benefit from the application and could vary in cost depending upon the availability of materials.

* Corresponding author.

E-mail addresses: santosh.yadav@3sr-grenoble.fr (S. Yadav), hala.damerji@3sr-grenoble.fr (H. Damerji), reinold.keco@univ-grenoble-alpes.fr (R. Keco), yannick.sieffert@3sr-grenoble.fr (Y. Sieffert), florent.vieux-champagne@univ-grenoble-alpes.fr (F. Vieux-Champagne), yann.malecot@3sr-grenoble.fr (Y. Malecot).

The use of timber in masonry structure as a seismic band was present from the Minoan Crete 2500 years BC [11], and the finding observed after the 2017 Lesvos Earthquake in Greece by [12] showed that structures with timber reinforcement suffered only localized damage and prevented them from complete collapse. The materials for such a band can be timber, reinforced concrete, bamboo, etc. But there is a lack of quantitative data, which prevent the efficiency comparison of different reinforcement technique [13] and without scientific experimental results, the behavior and performance cannot be assessed.

In this paper, the main idea is to reveal the traditional practice using seismic band placed during construction of building rather than repairing it after the damage as adopted by many countries and observed the crack opening in the masonry wall using the Digital Image Correlation technique. The quantitative pieces of information are obtained through two experimental samples, which can be useful for comparison and validation for the numerical model to carry out a parametrical analysis. This work is a part of a multi-scale experimental campaign to characterize seismic bands' behavior and then validate the numerical model developed at our laboratory.

In the following subsection 1.1, the background about the use of the seismic band, their recommendation as per various guidelines, and codes are included. Subsection 1.2 allows one to understand the major failure modes in masonry and appreciate the advantages of having a seismic band (subsection 1.3) in the masonry structure.

1.1. Seismic band

Seismic bands are a constructive device-specific to traditional masonry constructions in seismic zones. The first traces come from the Minoan period - the bronze age - in Crete [14]. Such a device consists of placing at a level of several horizontal joints from the ground level regularly spaced pieces of wood forming a kind of ladder that is "laid" lengthwise on the

masonry. Such bands may also be referred to as a ring beam in [15–19], but that is not always the case and depends on the connection between insertions. These elements can be continuous (above the openings) and look like a horizontal beam as shown in Table 1 (at lintel, roof, plinth level) or discontinuous (at the level of the openings) as shown in Table 1 (at sill level), even punctual (at the level of the angles). These inclusions are usually made of timber or reinforced concrete in fired or raw bricks (adobes) or stone masonry. Sometimes, one can also find longer stones used as a band in stone masonry. Nepal National Building Code [20] also mentioned using bamboo as a seismic band in NBC 203. Table 1 shows the recommendation for seismic band location and material that can be used for such band by different codes and guidelines for earthquake resistant design for masonry structures. As per our knowledge and finding, the various code's current provisions were prepared by the team of experts at International Association for Earthquake Engineering during 1980s [16] and consequently adopted by different countries.

Table 2 shows that longitudinal timber members' dimension has some variation, which might be due to construction and material restriction in the region. For a reinforced concrete band, all the guidelines and reference have the same recommendation for the dimension.

1.2. Failure modes

Usually, the interface is the weak bond between mortar and units in masonries. This low tensile strength creates a key reason for most of the damage [28]. Damage in the structure is directly influenced by the seismic event, which has its characteristics. Each seismic event is characterized by its horizontal and vertical ground motion components, which are influenced by the nature of fault rupture, the distance between source to site, ground condition, and magnitude [29]. The structures' failure pattern can vary depending on the nature of the material used, bond strength, normal axial loading due to roof and other superstructure on the wall, placement

Table 1
Guidelines with the recommendation for seismic band location and material.

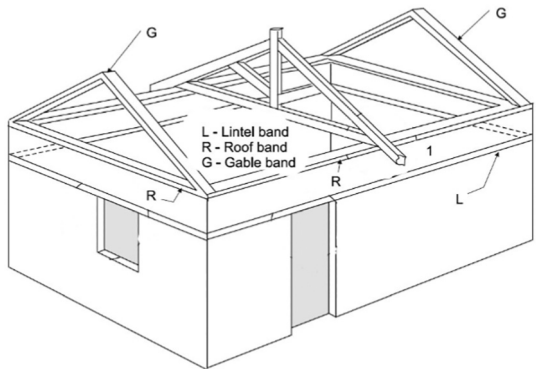
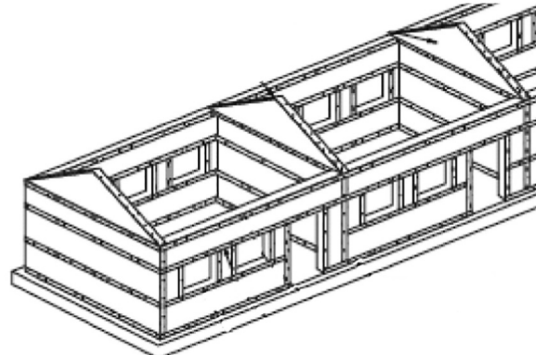
Guidelines and building codes	Seismic band material	Location
Guidelines for earthquake resistant non-engineered construction [16]	Reinforced concrete Timber	 <p>Lintel, Roof, and Gable</p>
Indian standard [21]		
UNESCO Guideline [15]		
Earthquake resistant Guidelines-Afghanistan [22]		
NBC 203, National Building Code- Nepal [23]	Reinforced concrete	 <p>Plinth, sill, lintel, roof, and gable</p>
Earthquake resistant Guidelines-Pakistan [24]	Timber	
Building reconstruction guidelines for Nepal [25]	Bamboo	

Table 2
Dimension specification for timber and reinforced concrete band.

Timber seismic band	Reinforced concrete seismic band
Longitudinal member Dimension: 75 mm × 38 mm [15,22,24,26]	75 mm thick with two longitudinal rebars 12 mm diameter
75 mm × 45 mm [25]	150 mm thick with four longitudinal rebars at lintel level
100 mm × 50 mm [27] Transverse member spacing = 500 mm	Tie spacing 150 mm c/c using 6 or 8 mm diameter rebar [15,20,22,24–27]

of opening, and seismic loading. Fig. 1 shows the global failure mode in a masonry structure when submitted by seismic loading action. However, these entire failure modes are not necessarily occurring during any event. In the case of an out-of-plane wall, the failure can be due to flexural bending or corner separation or the wall's delamination. For the in-plane wall, it could be due to diagonal shear crack, shear sliding, or flexural bending/rocking. Suppose the crack formation and propagation can be limited by any means. In that case, the structural damage can be minimized and, most importantly, save the people's lives during a seismic disaster event. One such technique is the use of the horizontal seismic band.

1.3. Advantages of seismic band

Several experimental campaigns were conducted by submitting a masonry structure with a seismic band to dynamic loading using a shaking table [31–33]. They highlighted some advantages of inserting seismic bands. Their integration in masonry structures helps to improve integrity and ductility. If regularly spaced, bands prevent crack propagation and are limited within the region separated by the seismic band [34]. Moreover, the creation of a fused interface contributes to dissipating energy with minor damage. The dissipated energy depends on the material used and the connection between elements (as observed with timber band) [35].

Having past evidence from the ancient traditional structure and some of the qualitative performance behavior of the seismic band application highlights the benefit of using it. But, few more question arises, when we check the available guidelines and codes of some nations. What should be the suitable thickness of the band? Does the spacing between the band matter? Is there any major change in the behavior when the material used as a band is changed? Answer to such questions requires rigorous analysis, which becomes difficult with the only experiment, and hence, the need for numerical modeling to carry out parametrical analysis plays a key role. The accuracy of the numerical model depends upon the constitutive laws and validation with the experimental results. Thus, our experimental campaign's objective is to obtain reliable information that addresses the structural behavior in a localized region and can help validate the numerical model in the future.

2. Materials and methodology

As per the reconstruction guidelines of Nepal [25], there are suggested using a vertical reinforcement bar at the corner and opening. However, from the study of [8], internal placement of vertical reinforcement proved

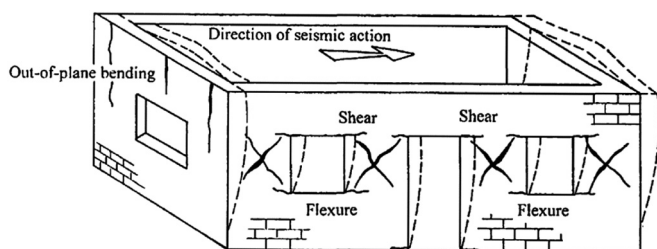


Fig. 1. Various failure mode in a masonry structure [30].

to create stress concentration and make the structure weak. Also, data from the site suggests difficulties in placing the vertical reinforcement bar. Therefore, we have considered a wallet-size sample with and without a band to determine in-plane behavior for this study. A quasi-static cyclic loading test is used to determine the influence of a horizontal seismic band in a masonry wall. The shear resistance of the wall can be obtained by applying the in-plane loading [36], but for this study, we have compared the crack surface area with the corresponding force rather than the classical hysteresis curve. The loading pattern was selected based on the recommendation of [37] for the quasi-static loading cycle. The general experimental setup is shown in Fig. 2, where the loading actuator/jack, camera setup, and specimen location are indicated. With the help of a C-shaped metallic connected to the actuator (graphically indicated in Fig. 3), it is possible to apply cyclic loading by changing the loading direction. Two masonry walls (dimension 0.91 m in length, 0.86 m in height, and thickness of 0.32 m) are built with and without a seismic band. Timber was used as a seismic band with a cross-section dimension of 70 mm × 50 mm and arranged in the form of the ladder as shown in Fig. 4 using nail connection. Earth (adobe) bricks are used to construct the walls using mud mortar with a thickness of 20 mm. A reinforced concrete stud is cast around the first brick bed, and a metallic strip is added to the ends, which is fixed using nuts and bolts. The compressive strength of brick-and-mortar ranges from 1.2 MPa to 1.4 MPa when tested individually, and with the compression test on the wallet, the average compressive strength of about 1 MPa was obtained. These values are necessary for determining the loading conditions for the test. A speckle pattern on the wall surface, which is needed for carrying out digital image correlation (DIC), is created using black and white aerosol spray paint. DIC was quite useful in the past few decades to get information at the local level without the use of any sensor on the specimen. The digital image correlation technique allows for a continuous record of cracks formation all along the displacement cycle.

A dead load of 9.8 kN is added on the top of the wall, representing that of a roof and any other structure supported by the wall. This dead mass is uniformly applied on the wall creating normal axial stress of 0.03 MPa. A cyclic displacement until a maximum amplitude of 80 mm is applied on the wall, as shown in Fig. 5, at a variable rate of displacement (see Fig. 6).

3. Results

Two masonry walls are quasi-statically loaded. The measurement of force recorded from the sensor associated with the jack and displacement recorded using the LVDT sensor at the top of the wall are used to generate a hysteresis curve, as shown in Fig. 7. From this plot, we observe that both walls' behavior is similar until 5 mm horizontal displacement, after which we notice changes in the nature of the curve. For the wall without the seismic band, the peak force value is increased more than the one with a timber band. However, the maximum displacement of the wall with the band is higher due to the wall's sliding behavior at the interface between the seismic band and the adobe brick.

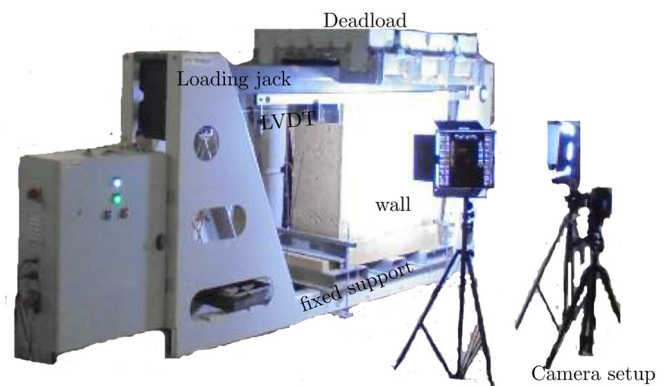


Fig. 2. General experimental set up for the quasi-static test.

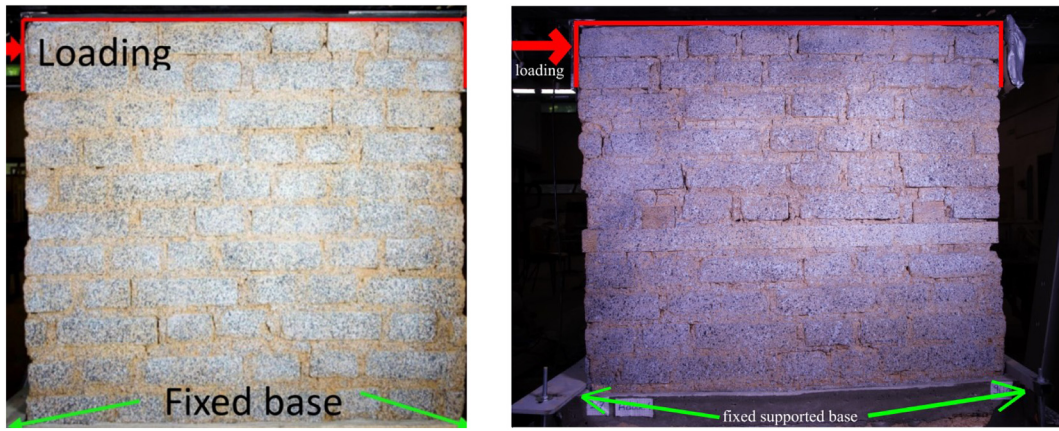


Fig. 3. Masonry wall without a band (left) and with timber seismic band (right).

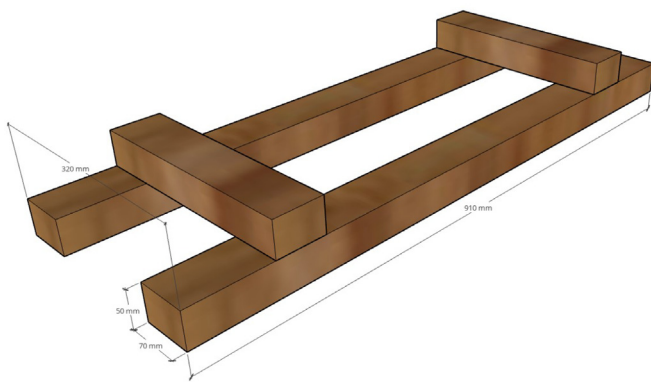


Fig. 4. Dimension of timber seismic band used.

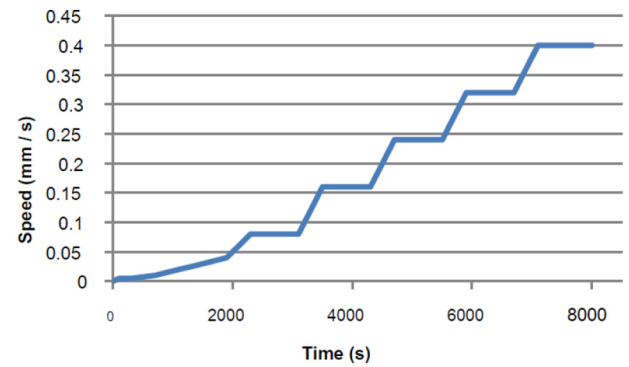


Fig. 6. Displacement loading rate.

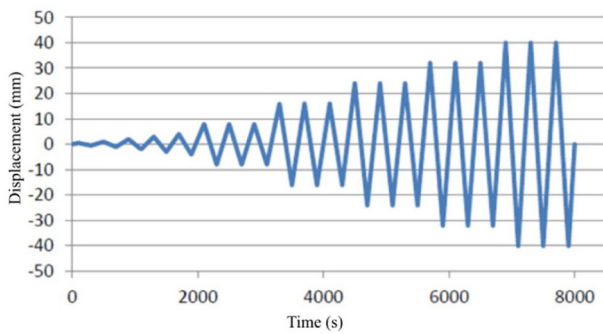


Fig. 5. Displacement sequence for the quasi-static cyclic tests applied to the jack.

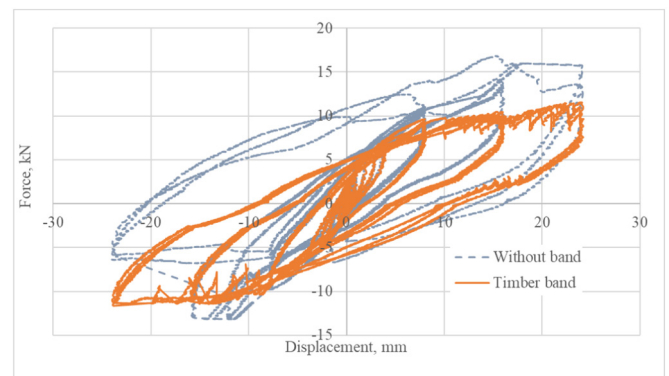


Fig. 7. force-displacement hysteresis curve.

Fig. 8 shows the same tests' envelope curves, which are constructed by taking the ultimate force values during the first cycle of targeted amplitude cycles and their corresponding displacement point. From this plot, we observe that the force value increases in both loading directions for the wall without band because the changing direction develops new crack/fissures in the sample. Whereas, for the wall with timber band, the force is higher during the first cycle with an increasing amplitude indicated by the negative force-displacement part of the curve. This phenomenon could be due to the sliding behavior at the interface of the band and brick joint.

The energy dissipation is calculated from the hysteresis curve, taking the area under the curve for three classified cycles (Fig. 10) and tabulated in Table 3. The values indicated here are the total energy dissipated by the global behavior of the wall. The value of energy dissipation by the

wall without band is more because of the more force required to reach the targeted displacement and more permanent damage on the wall.

The entire experiment is recorded with a high-resolution camera with images captured at an interval of 10 s. These images are later analyzed using the image-correlation software 'Tracker' [38]. The imaging was carried out for the only surface, but the crack propagation on both the surface was verified and observed uniformly regarding crack development. Each brick is associated with four points placed on its corners, forming quadrilateral, and the position of each brick is tracked image by image. The corner of the whole or fragmented brick was manually located by comparing the first image with the last one to avoid the error during DIC due to crack formation

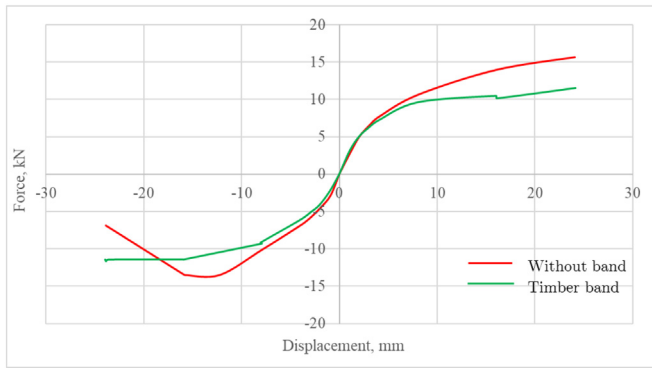


Fig. 8. Envelope curve for two wall samples.

Table 3
Energy dissipation from hysteresis curve.

	Energy dissipation, kN-mm	
	Without band	Timber band
Cycle 1	303	241
Cycle 2	848	605
Cycle 3	1653	1154

or missing part at the measurement point, which is the reason why the shape of the brick looks irregular, as seen in Fig. 9. The horizontal force's value applied on the wall at each stage is associated with the captured image in the analysis. Thus, results obtained with the two walls using DIC can be compared with the corresponding force applied at a particular instant. Fig. 9 shows the DIC output results plotted graphically using MATLAB.

As the loading in the horizontal direction is applied, the crack opening at header joints (vertical fissures) increases significantly. A process is established to evaluate the pattern of vertical cracks. Each crack is viewed as a quadrilateral made of four points, two from each side of adjoining bricks. Coordinates are calculated to enlarge the cracks only when there is a difference in the displacement values between two bricks. This displacement obtained from DIC is multiplied with the head or bed joint's length to calculate the surface area of fissures in a vertical or horizontal direction, respectively. For comparing the results of the two cases, it is important to consider deformation stages. For that, three cycles were chosen with constant displacement amplitudes, as shown in Fig. 10. The following analysis is carried out for each cycle using cracks surface area total variation in square

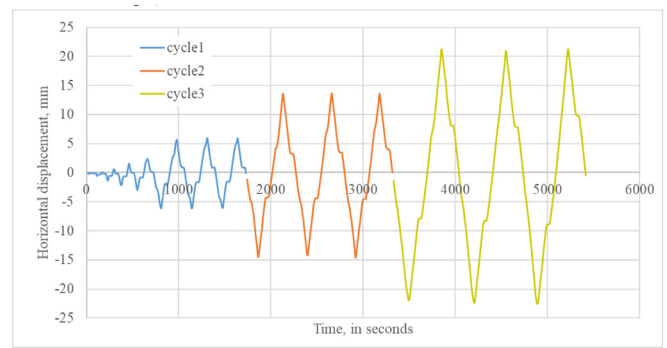


Fig. 10. Classification of displacement cycle for a wall with a band.

millimeters extending upwards in the y-axis direction, dependent on the force value in the x-axis direction. The x-axis consists of the force applied by the loading actuator. The positive part indicates pulling force (represented with positive force and displacement when the wall is moved towards the left), and the negative part indicated the pushing force (represented with negative force and displacement when the wall moves towards the right).

Four main observations can be done throughout the first loading cycle that is shown in Fig. 11. Here, the cycles are classified by the peak horizontal displacement applied to the walls, and each cycle indicated has three periods of oscillation. First, in the beginning, both walls have similar behaviors. Crack opening increases at a slow pace, and deformation is characterized by almost perfect elasticity. Bonding between bricks is still intact, so walls behave like an entire unit. Second, the wall with a horizontal band suffers 8-shaped fluctuations in the crack opening, which is due to cracks below the band that are enlarged and then closed again while slightly ripping and drifting towards permanent deformation. Third, when a force pushes the wall without a seismic band towards the right (force is negative in this case), we can see an obvious increase in the crack opening. It reveals the appearance of the first major diagonal crack in the wall without any band. We can observe sorts of steps, or a stair-like shape, while fissures jump from 100 mm² to around 520 mm². These sharp increases are the result of abrupt disconnections between certain bricks. Fourth, at the end of the first cycle, due to the newly formed crack, not much (negative) force is needed to impose displacement in the right direction. Then, the semi-detached block of bricks smoothly glides at every displacement cycle of constant amplitude.

During the second cycle (Fig. 12), a more regular evolution pattern is observed. The phenomena previously described during the first cycle seem to predefine the behavior during the second cycle. The previous

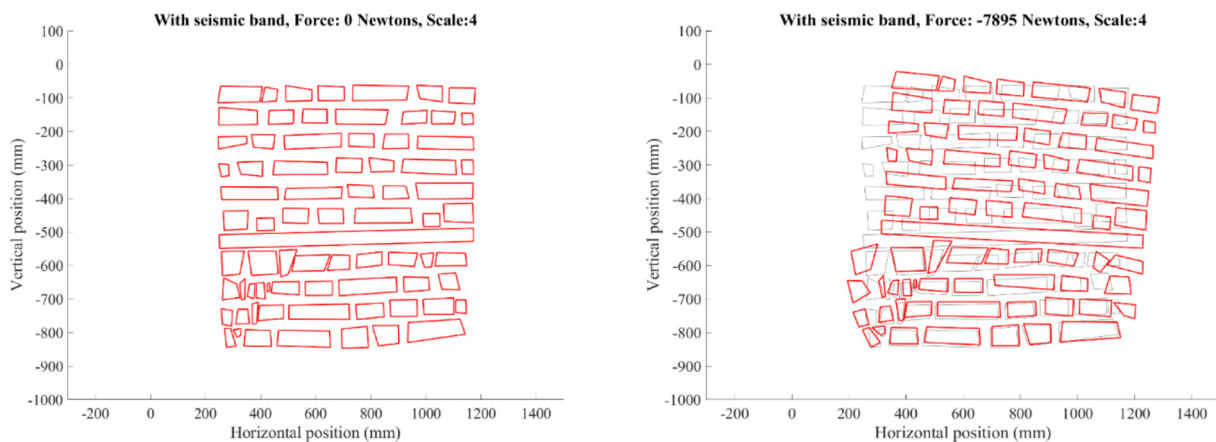


Fig. 9. DIC displacement output field for masonry wall with timber band at zero force (left) and 7.89 kN force (right).

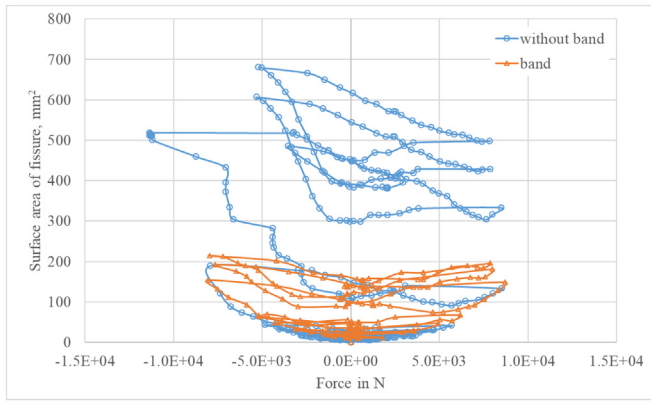


Fig. 11. Vertical fissure area in relation to the applied force during the first cycle.

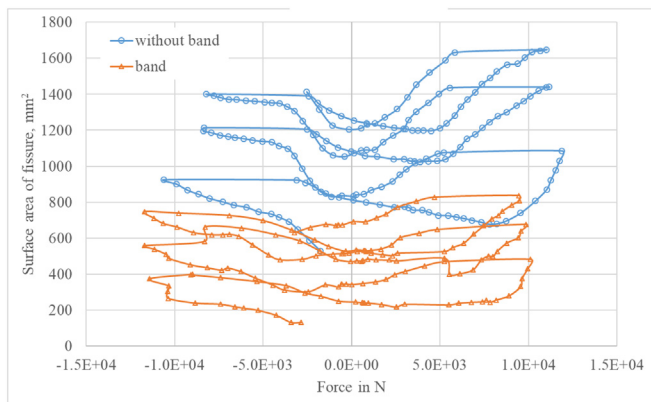


Fig. 12. Vertical fissure area in relation to the applied force during the second cycle.

loading cycle remnants are immediately noted; the surface area is around 200 mm² for the wall equipped with a band and around 680 mm² for the wall without any band at the beginning of the second cycle. The orange curve is smoother and narrower than the blue one. This shows a very gradual and stable enlargement of cracks between the bricks. On the other hand, the blue curve shows a less stable pattern.

For both the wall, the surface area of cracks increases way faster at every round. Secondly, a steep decline in the surface area of crack is noticed in every direction change of the applied force. That is because separated blocks slide back to their initial positions. Since the first crack was seen on the right side of the wall when the force is negative, both increase and decrease of crack opening follow the same trend. However, when the force is positive, the wall is pushed on the left, the first left-side cracks appear on the wall without any band. Therefore, the blue curve on the top right side of the graph increases a lot more than the orange one. The maximum surface area of fissures obtained during the second cycle is approximately 800 mm² and 1620 mm², respectively, for the wall with a band and without a band.

During the third cycle (Fig. 13), the behavior of the wall with the band is still the same, and the orange line follows the same trend as in Figs. 11 and 12. This means that integrity is preserved in a wall with the seismic band until the end of the third cycle of displacements. The same cannot be said about the behavior of the wall without any band. The blue line shows that the crack surface area seldom decreases in value. Older cracks expand, and new cracks in the wall's inner parts are created whenever the imposed force is at its highest. Another interesting thing to notice, in the case of the wall with a band, is that while force switches directions, the crack surface area remains almost constant. This happens because both the upper and

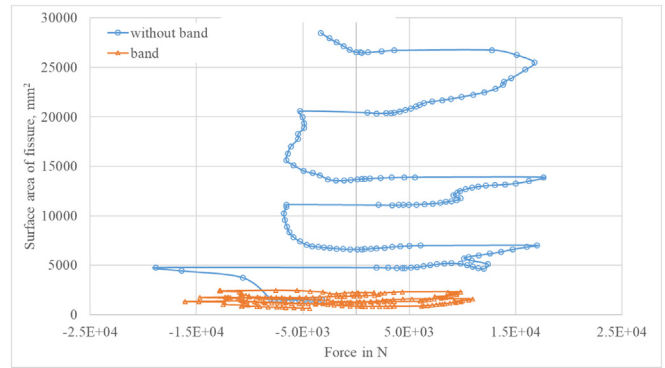


Fig. 13. Vertical fissure area in relation to the applied force during the third cycle.



Fig. 14. Wall with timber band at 4560 s of loading at peak displacement towards left.



Fig. 15. Wall with timber band at 4880 s of loading at peak displacement towards the right.

lower part of the wall has been disconnected at the band level, so instead of expanding, cracks simply shapeshift from rectangles into parallelograms (when pushed or pulled from the initial location) while covering the same surface as shown in Figs. 14 and 15.

4. Discussion

The results presented in this paper show a correlation between the dissipation energy and the amount of crack opening area. Indeed, the wall without a seismic band has both dissipation energy and a quantity of crack opening area much stronger than the wall with the seismic band. This result may seem counter-intuitive but perfectly logical because the seismic band limits the masonry's damage and makes it possible to locate the slip at its interface. Without a seismic band, the slip between the bricks is stronger, leading to both an increase in dissipation energy and a loss of structural stability of the whole. The higher crack area shows more damage to the masonry structural integrity. From this, one could conclude that the wall without the band tends to have several major cracks, which might increase the cost for retrofitting, if possible, in the structure after a seismic event. However, when the fissure surface area is small (as seen with the wall with a seismic band), the occupant's structural integrity and safety are maintained. Such structures can be easily retrofitted at a reasonable cost. The horizontal cracks have also been studied, but results are not conclusive, partly because the opening of horizontal cracks is low due to the axial loading caused by the dead mass on the wall's top. This phenomenon is also seen in the real structure where the gravitational load acting on the wall is high, and the seismic signal has significant horizontal components.

The failure occurred through the mortar joints and propagated along the horizontal and header joint. Some of the bricks were fragmented during the crack propagation, as seen in Figs. 14 and 15.

5. Conclusions

The crack opening size below 50% of ultimate displacement stays similar in both the walls (with or without timber band). After that limit, we have a bigger crack size for the wall without a band. Such cracks are not visible easily, but thanks to the DIC technique, we can capture the small variation in the displacement, which helps understand why there was a drop in the value of force after each cycle's first peak. For a wall sample with a timber band, the cracking opening change is gradual, contrary to that of the wall without a band. In the wall with a horizontal seismic band, the crack was formed in the lower part, which did not propagate to the upper part. This also highlights the benefit of a seismic band in limiting the crack, and once the crack reaches the interface with the band, it propagates horizontally, leading to a sliding mechanism between the interface of the band and the adjacent masonry layer, which helps in energy dissipation. The results of a comparison of two walls with respect to the crack opening and corresponding force are helpful to understand the shear behavior of the wall from a distinct perspective apart from the hysteresis curve, where we cannot have a detailed illustration of behavior and crack formation.

6. Perspectives

We studied the influence of the horizontal loading applied quasi-statically on the wall with and without a timber seismic band on crack opening size during this study. But further studies are needed with the use of the RC band and to figure out how such a band influences the structure's behavior. In design code, mostly horizontal seismic force is only considered, but there are some events where the vertical ground motion becomes significant. Therefore, the study on such band behavior needs to be made for both horizontal and vertical components. It would be interesting to extend the study to other types of interface material such as reinforced concrete and bamboo as per different guidelines. The preliminary study [35] shows that sliding and energy dissipation depends on the material and its surface roughness and connection type. Therefore, it is important to carry out a similar test with other materials to verify the benefits of having such a band. From this study, we saw the crack propagation, and damage in a wall with timber seismic band was limited in the bottom part (see Fig. 9). What will happen when several such sections are separated with multiple layers of the band must be investigated.

Moreover, structural behavior varies during quasi-static and dynamic loading. In the real scenario, the earthquake loading is dynamic where the damping and inertial force play a key role. Therefore, it is also necessary to investigate the seismic band's performance when impacted by dynamic loading using shaking table tests and numerical modeling for parametrical analysis. In our multi-scale experimental campaign, we are going to test the reduced scale house model using seismic band under dynamic shake table test, more quasi-static test using wallet sample, shear behavior at the interface, along with material property characterization. Similarly, we are developing a numerical model developed using a macro element that will use our experimental results and then carry out parametrical analysis of the whole house structure.

Author statement

Florent Vieux-Champagne, Eugénie Crété, and Yannick Sieffert: conceptualization; methodology; writing-review & editing. Yannick: project administration; software Santosh Yadav, Hala Damerji, and Reinold Keco: formal analysis; investigation; validation; visualization. Santosh Yadav: writing-original draft, writing-review & editing. Yannick Sieffert, Philippe Garnier, and Yann Malecot: supervision; funding acquisition; writing-review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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